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THERMAL AND FLOW ANALYSIS OF A CONVECTION, AIR-COOLED CERAMIC COATED POROUS METAL CONCEPT FOR TURBINE VANES

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ABSTRACT

Analysis was made of the heat transfer and pressure drop through turbine vanes made of a sintered, porous metal coated with a thin layer of ceramic and convection cooled by spanwise flow of cooling air. The analysis was made to determine the feasibility of using this concept for cooling very small turbines, primarily for short duration applications such as in missile engines. The analysis was made for gas conditions of approximately 10 and 40 atm and 1644 K (2500° F) and with turbine vanes made of felt-type porous metals with relative densities from 0.2 to 0.6 and ceramic coating thicknesses of 0.076 to 0.254 mm (0.003 to 0.010 in.).

NOMENCLATURE

A	area
c	specific heat at constant pressure
D	porous metal relative density
d	equivalent pore size
h	heat-transfer coefficient
k	thermal conductivity
L	vane airfoil span
l	increment of airfoil span length
Nu	Nusselt number
ΔP	pressure drop
Pr	Prandtl number
p	pressure
q	heat flux
Re	Reynolds number
T	temperature
ΔT	temperature rise
V	velocity
w	flow rate
x	distance from leading edge
Z	chordwise length of element analyzed
α	ratio of porous metal internal surface area volume
δ	thickness of chord element analyzed
ρ	density
μ	viscosity
τ	ceramic thickness
ψ	porosity

Subscripts

a	cooling air
b	ceramic thermal barrier
p	porous metal
g	hot gas
o	gas side surface

INTRODUCTION

The performance of small gas turbines such as used for missile propulsion are presently limited by the gas temperatures at which uncooled parts can survive. These turbines are presently not cooled because of the difficulties and cost of incorporating coolant passages into the very small hardware. Convection air-cooling of parts made of ceramic coated sintered porous metal is a concept that may not be too difficult or costly to fabricate and which may permit increases in gas temperatures. In this concept the cooling air flows spanwise through porous vanes or blades. The sides of the porous metal parts adjacent to the hot gas are sealed by a metallic bond coating and are thermally insulated by a thin ceramic layer. No air transpires through gas-side surfaces. The ceramic coating is of the plasma sprayed-on type described by Liebert and Stepka (1) and Stepka (2). The somewhat compliant porous metal core can, according to results obtained by Bill, Wisander, and Brewe (3) mitigate the expected strain differences between the ceramic layer and metal core and provide for good ceramic coating adherence.

Although porous metals have been advocated for transpiration-cooled gas turbines, their use has been constrained by the concern for the clogging of the small pores by contaminants in the cooling air and by oxidation of the surfaces that would be expected after the thousands of hours of operation required of aircraft engines. Other than reference 4 the author has no knowledge of the consideration of use by others of convection-cooled porous metal turbine parts. The concern for clogging of the small pores still exists for engines where extended operation is required. However, for the application of concern herein, where the mission or expected life is only about 10 hours clogging would not be a problem, and oxidation could be minimized by limiting the maximum porous metal temperature.

The purposes of this paper are to analyze the feasibility of using the described concept on a turbine vane as related to heat-transfer and cooling-air pressure drop and to evaluate the influence of some of the variables that are expected to affect the performance of the concept.

One-dimensional flow and heat-transfer analyses were made across an element of turbine vane span made of a porous metal and coated on the gas side by a ceramic. The analyses determined the spanwise temperatures of the ceramic and porous metal and spanwise coolant-temperature rise and pressure drop through the vane. The analysis was made for gas conditions of approximately 10 and 40 atm and 1644 K (2500° F) and for cooling air bled from the compressor exits. The vanes were considered to be made from either of two felt-type sintered porous metals with different structure and pressure drop characteristics and with relative metal densities of 0.2 to 0.6 (metal porosities of 0.8 to 0.2). The ceramic coating was yttria stabilized zirconia with thicknesses of 0.076 to 0.254 mm (0.003 to 0.010 in.). The results are presented in terms of the spanwise temperatures of the ceramic gas side surface, the porous metal, and the coolant for changes in the magnitude of the variables investigated. Also indicated are spanwise locations at which maximum allowable cooling air pressure drops were reached.

ANALYSIS AND CONDITIONS

Composite Configuration

A schematic of the ceramic coated porous metal concept as applied to a small turbine vane is shown in Fig. 1. A typical chord for these small turbine vanes is about 2 cm and the span is about 1 to 2 cm. In this application the vane or group of vanes would be fabricated of the sintered porous material and then coated with a thin metallic bond layer and then with the ceramic layer. For the purpose of the analysis herein, the thickness of the metallic bond coating was neglected. Also for the purpose of this analysis, the properties of the ceramic were assumed to be those of a plasma sprayed coating. The cooling airflow in this application was assumed to enter at the vane root, flow spanwise, and then exit at the vane tip. No flow exits through the gas-side surface since it is assumed sealed by the bond coating. The thickness, δ, of the element of the airfoil analyzed was 3 mm (0.12 in.). The ceramic thickness was assumed to be either 0.076, 0.127, or 0.254 mm (0.003, 0.005, or 0.010 in.).

Composite Properties

In conducting the heat-transfer and pressure-drop analysis, certain properties of the porous metal and ceramic were required. Equations were evolved which fit available data from a fabricator of porous materials. Two porous materials, designated herein as PM-1 and PM-2, were considered. The difference in the porous metals was the fiber aggregate. The fiber of PM-1 was thinner and shorter than that of PM-2, and PM-1 had higher pressure-drop characteristics than PM-2.

The curve-fit equations for the equivalent pore size or diameter, d, are

$$d = 1.0\times10^{-4} \exp(-5.0\ D) \quad \text{for PM-1} \tag{1}$$

$$d = 5.75\times10^{-4} \exp(-4.3\ D) \quad \text{for PM-2} \tag{2}$$

where D is the porous metal relative density. The density, D, is related to porosity given by

$$\psi = 1 - D \tag{3}$$

The equations for the porous metal internal surface area to volume ratio, α, are

$$\alpha = 4.43\times10^{5}\ D \quad \text{for PM-1} \tag{4}$$

$$\alpha = 7.2\times10^{4}\ D \quad \text{for PM-2} \tag{5}$$

The porous-metal thermal conductivity, as obtained from (5) was assumed, for lack of other data, to apply to both porous materials:

$$K_p = 4.5\ D^{1.38} \exp(5.4\times10^{-4}\ T_p) \tag{6}$$

where T_p is the average porous metal temperature in kelvins.

The effective cooling-air cross-sectional flow area normal to the cooling-airflow direction was not available. However, for the purposes of this analysis it was assumed for both porous materials that the porosity (or void area) was uniform in all directions. With this assumption, and the definition of ψ, consideration of an incremental length, ℓ, of the total cross-sectional area, $Z\delta$, of the porous metal normal to the cooling air flow direction (Fig. 1), one obtains

$$\psi = \frac{\text{Void volume}}{\text{Total volume}} = \frac{\left(\sqrt[3]{\psi}\,\ell\right)\left(\sqrt[3]{\psi}\,Z\right)\left(\sqrt[3]{\psi}\,\delta\right)}{\ell Z\delta} \tag{7}$$

The product of the last two terms in the numerator is the effective flow area, A_a, so that by rearranging equation (7) and the use of equation (3), the following equation was obtained for the effective cross-sectional flow area:

$$A_a = (1 - D)^{2/3} \delta Z \tag{8}$$

The thermal conductivity of the ceramic thermal barrier coating was as obtained from (2),

$$K_b = -1.597 + 0.011\ T_b - 1.896\times10^{-5}\ T_b^2 + 1.324\times10^{-8}\ T_b^3 - 3.077\times10^{-12}\ T_b^4 \tag{9}$$

where T_b was average ceramic temperature in kelvins.

Heat Transfer

The element of the turbine vane made of the ceramic coated porous metal that was analyzed is shown in Fig. 1. The heat flow was assumed one dimensional through a unit span length of the vane, and radiation from the gas was neglected as was conduction to other parts of the engine. The average effective gas and cooling-air temperatures at each span position were assumed equal to the respective total temperature T_g and T_a. For this analysis T_g was assumed constant along the span. Also, because of the low heat flux expected by use of the ceramic coating and low coolant flow velocities required to avoid excessive pressure drops, near thermal equilibrium between the porous-metal and cooling-air temperature were expected. Furthermore, the small thickness, δ, of the vane combined with the results of the analysis of Koh and Colony (6) show that for low ratios of heat sink to heat conduction $(\rho_a V_a c_a \delta / k_p)$ the temperature gradient through the thickness is expected to be small.

As a consequence an assumption is made that the average T_p, for each increment of span length is equal to the ceramic porous metal interface temperature at that increment. For these assumptions the equations for the heat flux through each incremental length of span, ℓ, and a unit length of chord Z are

$$q = 2h_g Z\ell(T_g - T_{bo}) = 2\frac{k_b}{\tau} Z\ell(T_{bo} - T_p) = h_o\alpha(Z\ell\delta)(T_p - T_a) = w_a c_a \Delta T_a \tag{10}$$

where the terms are defined in the NOMENCLATURE section.

The gas-to-blade heat-transfer coefficient h_g was determined by using the equation for turbulent flow over a flat plate

$$h_g = 0.0296\ Re_g^{0.8}\ Pr_g^{1/3}\ k_g/x_g \tag{11}$$

where the Reynolds number Re_g was evaluated at the assumed engine conditions for a distance x_g from the leading edge of 6.3 mm (0.25 in.) and for an assumed Mach number of 0.4. The transport properties were evaluated using the data of Hippensteele and Colladay (7). The cooling-air temperature, T_a, was the arithmetic average of the air temperature into and out of each incremental length of span.

No internal heat-transfer coefficient data were available for the specific porous materials considered in the analysis. Instead, one of the equations describing the data for various porous metals in Koh, Dutton, and Benson (8) was used. The equation selected, in the notation of this report, was

$$\frac{Nu_a}{Pr_a^{1/3}} = 4 + 0.11\ Re_a \tag{12}$$

or

$$h_a = (4 + 0.11\ Re_a)Pr_a^{1/3}\ k_a/d \tag{13}$$

where the coolant-side heat-transfer coefficient, h_a, was based on the internal surface area of the porous metal. The coolant Reynolds number, Re_a, had as its characteristic the pore size d. The transport properties of air were evaluated using the data of Hippensteele and Colladay (7).

Equations (10) were used in a computer program to calculate the heat flux, q, the ceramic thermal barrier gas-side surface temperature, T_{bo}, the porous metal temperature, T_p, and the coolant temperature rise, ΔT_a, and the average coolant T_a temperatures, at each incremental length, ℓ, of the span. These calculations were made for each of several values of implied coolant flow rates w_a based on assumed coolant inlet flow Mach numbers.

Based on considerations of low oxidation, the maximum allowable T_p was assumed to be 1200 K (1700° F). It was this maximum allowable temperature or the maximum allowable air pressure drop (discussed in the next paragraph) that limited the span length of the vane that could be used.

Pressure Drop

The cooling-air pressure drop within the porous material was calculated for each incremental span length and then summed up for each additional incremental length ℓ to obtain the total pressure drop. The maximum allowable value of the total pressure drop for the porous metal at each engine condition analyzed was arbitrarily assumed to be one-fourth of the supply pressure.

Equations to calculate the cooling-air pressure drop at standard atmospheric conditions were obtained from curve fitting of the data supplied from the porous metal fabricator and included the effects of porous metal thickness, porous metal density, and flow velocity. Then the equations were modified to include the effects of air viscosity by use of the Darcy equation (from Carmin (9)). The equations for cooling pressure drop for each increment of span length were

$$\Delta P_a = 7.6\times10^7\ V_a \mu_a \ell\ \exp(11.2\ D)\ \mathrm{N/m^2} \quad \text{for PM-1} \tag{14}$$

$$\Delta P_a = 2.0\times10^6\ V_a \mu_a \ell\ \exp(11\ D)\ \mathrm{N/m^2} \quad \text{for PM-2} \tag{15}$$

Engine Conditions

The ceramic coated porous metal turbine vane was analyzed for conditions expected in an engine with a moderate and one with a high compressor pressure ratio of 10 and 40 atm, respectively. The turbine-inlet gas temperature for both engines was assumed to be 1644 K (2500° F). A total-pressure drop of 6 percent across the combustor was assumed to obtain the turbine vane inlet gas total pressure. The coolant-air total pressure at the turbine vane root was assumed equal to that at the compressor exit. The vane cooling-air inlet total temperatures were equal to that at the compressor exits assuming a compressor adiabatic efficiency of 0.95. The assumed conditions are shown in Table 1.

RESULTS AND DISCUSSION

Selected plots of spanwise temperature, for the air-cooled porous metal turbine vanes analyzed are shown in Figs. 2 to 6. The data are presented for porous metals with two different internal structures with a range of porous metal relative densities (or porosities) and with a range of ceramic thermal barrier thicknesses and cooling-air inlet Mach numbers. The two porous metals are designated PM-1 and PM-2. The results are presented for the vanes in gas environments of approximately 10 and 40 atm at a gas temperature of 1644 K (2500° F).

Porous Metals Without a Ceramic Coating

The initial calculations were made to determine the performance of porous metal vanes with only the sealing metallic bond coating.

The changes in spanwise cooling air temperatures and metal temperatures with changes in cooling-air inlet Mach number for these vanes are shown in Fig. 2. The results show that for the low air inlet Mach number and large coolant-side (internal) surface area, T_a and T_p are essentially identical.

Figure 2(a) shows data for PM-1 with a 0.2 relative density at the 10-atm gas condition. The figure shows that the allowable maximum T_p of 1200 K (1700° F) is reached within 0.7 cm of the span when the cooing-air inlet Mach number was 0.005 (inlet Reynolds number, $Re_a \approx 16$). When the flow was increased to an air inlet Mach number of 0.01 ($Re_a = 36$) the maximum allowable T_p and the maximum allowable air pressure drop occured at slightly less than 1.2 cm of the span length. At a higher cooling air inlet Mach number of 0.02 ($Re_a = 75$) T_p is reduced but in less than 1 cm of span length the maximum allowable pressure drop is reached.

In Fig. 2(b) results are shown for the same porous material at the 40 atm gas condition. The figure shows that at an inlet Mach number of 0.01 and 0.02 ($Re_a = 98$ and 200) the maximum T_p is reached in about 0.9 and 1.9 cm, respectively, without reaching the allowable maximum pressure drop. For the air inlet Mach number of 0.02 it can be seen that the allowable pressue drop limit would have been reached at the span length of 2.2 cm. Increasing the Mach slightly above 0.02 would cool 2 cm of the span without exceeding the allowable air pressure drop. As the air Mach number is increased to 0.05 ($Re_a = 511$) the pressure-drop limit would be reached in a span length of about 1.3 cm at $T_p = 900$ K.

Figure 3 shows the effect of cooling-air inlet flow Mach on porous metal PM-2 with a relative metal density of 0.4 (or porosity of 0.6). The higher metal density was chosen for this illustration because the higher porous metal density is related directly to increased material strength. Also, PM-2 has lower pressure drop characteristics than PM-1, permitting it to be used at higher metal densities.

Figure 3(a) shows that at 10 atm almost 2 cm of the span can be cooled below the 1200 K allowable metal temperature limit at a air Mach number of 0.02 ($Re_a = 170$) without exceeding the pressure drop limit. At a Mach number of 0.03 ($Re_a = 260$), 2 cm of the span can be cooled to less the 1050 K. At this span length, however, the allowable pressure drop limit would be reached.

Figure 3(b) shows that at the 40-atm gas condition no pressure drop limit exists for air inlet Mach numbers from 0.01 to 0.05 ($Re_a = 223$ to 1169). At these conditions at least 3 cm of the span can be cooled below the allowable metal temperature without exceeding the pressure-drop limit.

In summary, porous metal vanes made of PM-1 with a relative density of 0.2 (or porosity of 0.8) and without a ceramic coating can be adequately convection cooled to span lengths of 1.2 and 2 cm at 10- and 40-atm gas pressures, respectively, and at a 1644 K gas temperature. Although not shown in the figures, calculations show that PM-2, which has about one thirty-eighth the pressure drop of PM-1, at a relative metal density of 0.2 can be cooled to at least 3 cm of span length without exceeding the allowable pressure limit at both the 10- and 40-atm gas-pressure conditions. Even at a relative porous metal density of 0.4, PM-2 can be cooled to at least 2 cm and 3 cm at the 10- and 40-atm gas pressures, respectively.

Effect of Ceramic Thickness

The effects of the ceramic thermal barrier thickness on the porous metal vanes of PM-1 with a 0.2 relative metal density and at a cooling air inlet Mach numer of 0.02 are shown in Fig. 4. The figure shows that the use of the ceramic significantly reduces porous metal temperatures. For example, Fig. 4(a) shows that a ceramic thickness of 0.127 mm (0.005 in.) can reduce the metal temperature by about 210 K at 1.2 cm from the vane inlet at the 10-atm gas-pressure conditions. For higher heat flux conditions at 40-atm gas pressure, Fig. 4(b) shows that the insulating benefit of the ceramic are larger. The figure shows that at an air inlet Mach numer of 0.01 ($Re \approx 100$) and at the 1.2 cm-span location, a 0.127 mm (0.005 in.) thickness of the ceramic reduced the metal temperature of a vane without a ceramic coating by 260 K. Figure 4(b) also shows that since the cooling air flow is not pressure drop limited, use of increasing thicknesses of the ceramic permits longer span lengths to be cooled without exceeding the maximum allowable porous metal temperature of 1200 K. At a ceramic thickness of 0.254 mm (0.010 in.) at least 3 cm of the span can be cooled below the maximum allowable temperature.

It should also be noted that the reductions in the porous metal temperatures by the ceramic are accompanied by large thermal gradients through the coatings. For example, at span locations near the vane inlet, the temperature difference across the 0.127 mm (0.005 in.) ceramic was about 450 K (810 F°) at the 10-atm gas conditions and about 560 K (1008 F°) at the 40-atm gas conditions.

Effect of Porous Metal Density

Figure 5 shows the effect of the density of porous metal at the 10-atm gas condition. For PM-1 with a 0.0127-mm (0.005-in.) ceramic at an air inlet Mach numer of 0.01, Fig. 5(a) shows that the change in spanwise porous metal, air, and ceramic gas-side surface temperature was small between densities of 0.2 and 0.3. However, the span location at which the maximum allowable air pressure drop is reached decreased from about 1.5 cm for the 0.2 density metal to an unacceptably small span length of about 0.5 cm for the 0.3 density.

For PM-2 with a ceramic coating thickness of 0.127 mm (0.005 in.) and at a cooling air inlet Mach number 0.02, Fig. 5(b) shows an increase of about 100 K in porous metal temperature at 1.5 cm of span as the relative metal density changed between 0.2 and 0.5. The figure also shows no air pressure drop limit for the relative metal densities of 0.2 and 0.3. As the relative metal density is increased to 0.4, the pressure drop limit is reached at 2.7 cm of span length. Then as the relative density is increased to 0.5 the allowable pressure limit is reached at 1.2 cm of span length.

Figure 6 shows the effect of material density at the 40-atm gas conditions. Figure 6(a) shows that because of the larger air-pressure drop available at this condition, the density of PM-1 could be increased to 0.3 at an inlet air Mach number of 0.005 and still cool over 1 cm of span length before exceeding allowable metal temperature. At a density of 0.4 and 0.5 only about 1 cm and 0.4 cm, respectively, could be cooled before exceeding the allowable pressure drop. Figure 6(b) shows that no pressure drop limit occurred with PM-2 at an inlet air Mach number of 0.01 even at relative metal densities as high as 0.6. Even at the density of 0.6, a span length of 1.6 cm can be cooled to less than the allowable metal temperature of 1200 K.

Since material structural strengths are generally directly related to the material relative density, the results of this analysis would indicate that PM-1 would not be acceptable for the 10-atm gas-pressure conditions if structural strengths required are greater than possessed by the 0.2 relative density material. This is because unacceptably short span length lengths of 0.5 cm or less could only be cooled without exceeding the allowable pressure drop with only an increase in density to 0.3. PM-2 however can be used to densities as high as 0.4 and 0.5 and still cool acceptable span lengths for the turbine.

At the 40-atm gas-pressure conditions, because of higher available pressure drop, PM-1 could marginally be used with a relative density of 0.4. At this density it could be cooled to about 1 cm of span before reaching the allowable pressure drop limit. PM-2 could be used at a relative density as high as 0.6 and cooled to acceptable span lengths.

SUMMARY OF RESULTS

The analysis of a convection air-cooled ceramic coated porous metal concept for turbine vanes showed the following:

1. Despite an initial concern for large cooling air pressure drops through the porous metal, the concept can be used for small-span turbine vanes at gas conditions of 10 and 40 atm and 1644 K (2500° F) without exceeding allowable cooling air pressure losses.

2. For some porous materials and operating conditions, (excluding consideration of structural strength) the concept may be used without a ceramic coating. For example, porous metal designated PM-1 with a relative density of 0.2 (porosity of 0.8) without a ceramic coating can be cooled to 1200 K (1700° F) to 1.2 and 2.0 cm of span length before exceeding its pressure drop limit at the 10 and 40 atm gas conditions, respectively. Porous metal designated PM-2 (with about one thirty-eighth of the pressure drop of PM-1) can be cooled to at least a 3-cm span length for both gas-pressure conditions.

3. The use of the ceramic significantly reduces the metal temperature at a given span location for a fixed cooling air low rate. For PM-1 with a relative metal density of 0.2 and with the cooling air inlet Mach number of 0.01 ($Re \approx 100$), a 0.127 mm (0.005 in.) thickness of ceramic can reduce the metal temperature by as much as 260 K (468 F°) at the 40 atm gas conditions. This metal temperature reduction occurs because of the large temperature drop (as much as 560 K (1008 F°)) across the thickness of the insulative ceramic coating.

4. The use of relatively low coolant-flow Mach and Reynolds numbers to limit cooling-air pressure drops and the large internal surface area resulted in the porous metal temperatures being essentially the same as the cooling-air temperatures along the span.

5. The influence of porous metal density on metal temperatures is not very large. At the 10 atm gas-pressure conditions and a cooling air inlet Mach number of 0.02, the metal temperature at the 1.5 cm span location on the vane changed by 100 K (180 F°) for a change in relative porous metal density of PM-2 from 0.2 to 0.5.

6. Since porous metal relative strength is generally related to its relative density, requirements of increased density may restrict use of materials with pressure drop characteristics similar to PM-1. For example, at the 10-atm gas-pressure conditions, PM-1 with a relative metal density of 0.3 could only be cooled to an unacceptably short 0.5 cm. PM-2, on the other hand, even at a relative metal density of 0.5 could be cooled to about 1.2 cm.

CONCLUDING REMARKS

The simplified analysis conducted herein which utilized some existing properties of porous materials and required assuming others, provided an initial indication of the feasibility of air cooling of ceramic coated, porous-metal small turbine vanes. The analysis also provided an initial evaluation of the significance of some of the parameters. The results of the analysis in general showed that the porous material with the lower pressure-drop characteristics, designated PM-2, was more desirable since longer span length could be cooled without exceeding the allowable pressure drop, particularly for the higher strength, higher density porous metals. The results also showed that the material density in the range of interest (0.2 to 0.6) did not result in a very large change in the cooling performance. Consequently, the choice of material structure and density will be to a large extent dictated by the porous metal strength capabilities and requirements and by the durability and adherence of the ceramic coating. Information in these areas are needed. Also, the necessity to assume heat-transfer and pressure characteristics for the porous metals indicates that additional experiments are needed on specific felt metal type porous metals to better characterize their performance. By obtaining equations that characterize these specific metals, a more accurate selection and optimization of desired properties for given applications can be made.

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TABLE I. - CONDITIONS ANALYZED

	Engine compressor pressure ratio	
	10	40
Turbine inlet gas total temperature, K (°F)	1644 (2500)	1644 (2500)
Turbine inlet gas total pressure, atm	9.4	37.6
Cooling air inlet total temperature, K (°F)	537 (507)	776 (936)
Cooling air inlet total pressure, atm	10	40
Maximum allowable cooling air pressure drop	2.5	10
Maximum allowable porous metal temperature, K (°F)	1200 (1700)	1200 (1700)

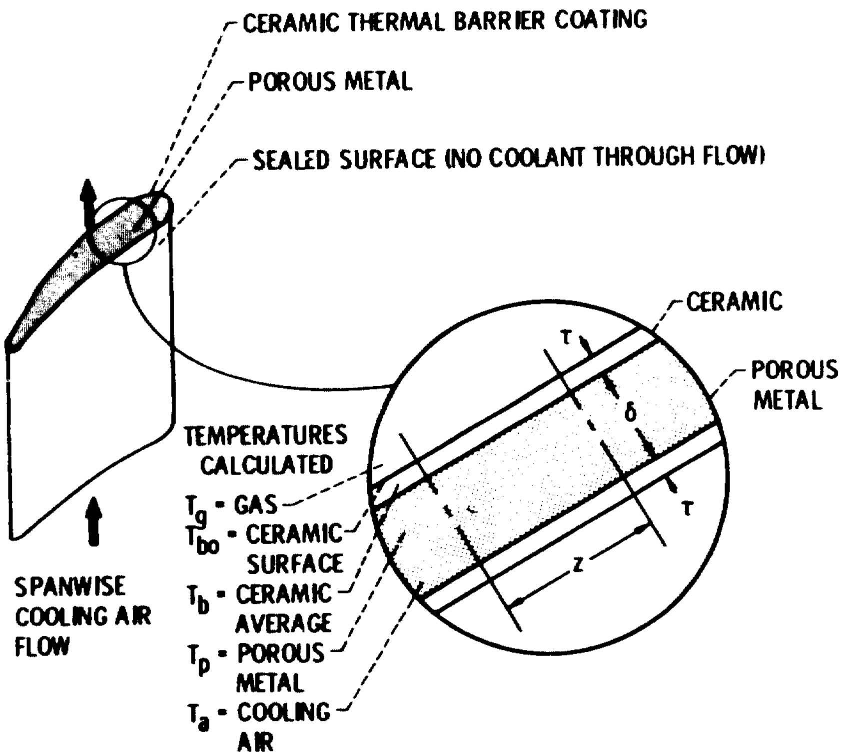

Fig. 1. Schematic of ceramic coated porous metal turbine vane.

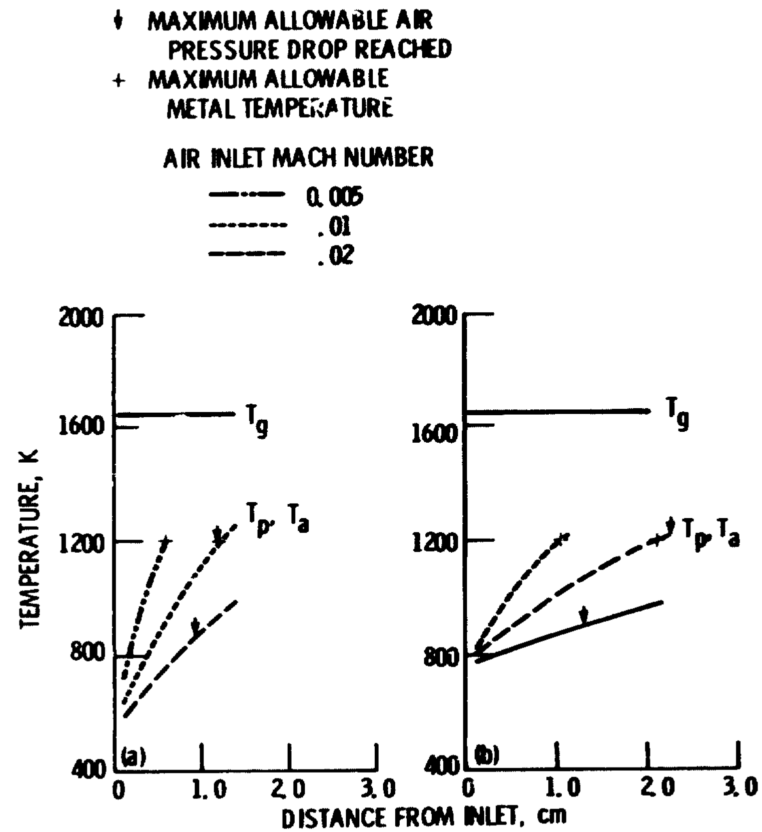

Fig. 2 Effect of cooling air inlet Mach number on spanwise temperatures of air-cooled porous metal vanes made of PM-1 with a metal density of 0.2 and without a ceramic coating. Turbine inlet gas temperature, 1644 K.

(a) Gas pressure, 10 atm.

(b) Gas pressure, 40 atm.

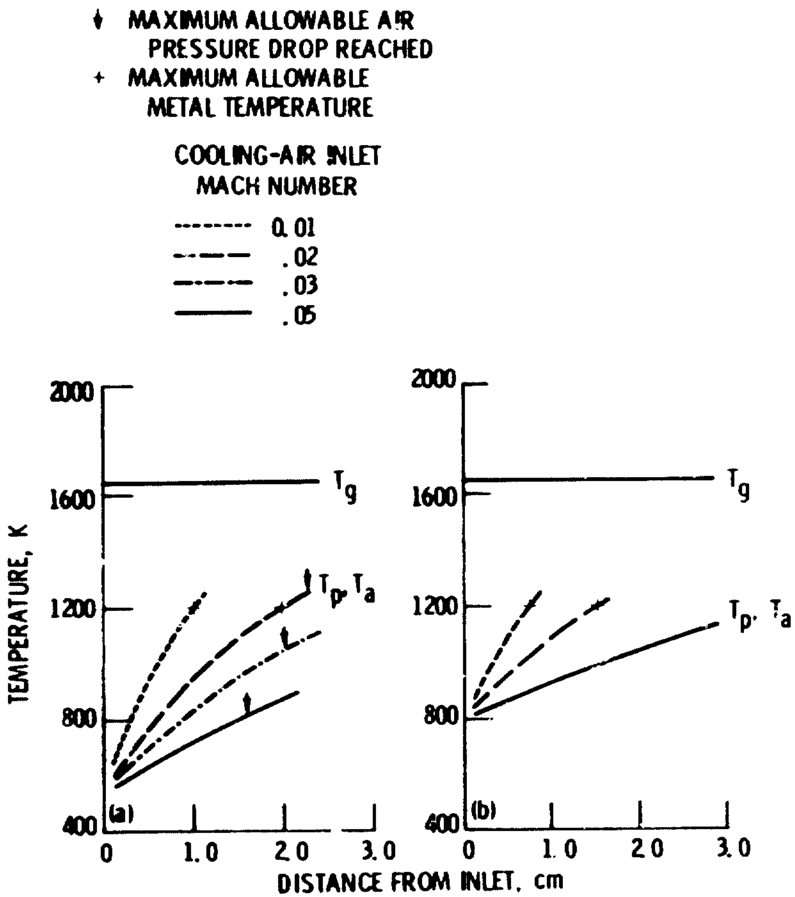

Fig. 3. Effect of cooling air inlet Mach number on spanwise temperatures of air-cooled porous metal vanes made of PM-2 with a metal density of 0.4 and without a thermal barrier coating. Turbine inlet gas temperature, 1644 K.

(a) Gas pressure, 10 atm.

(b) Gas pressure, 40 atm.

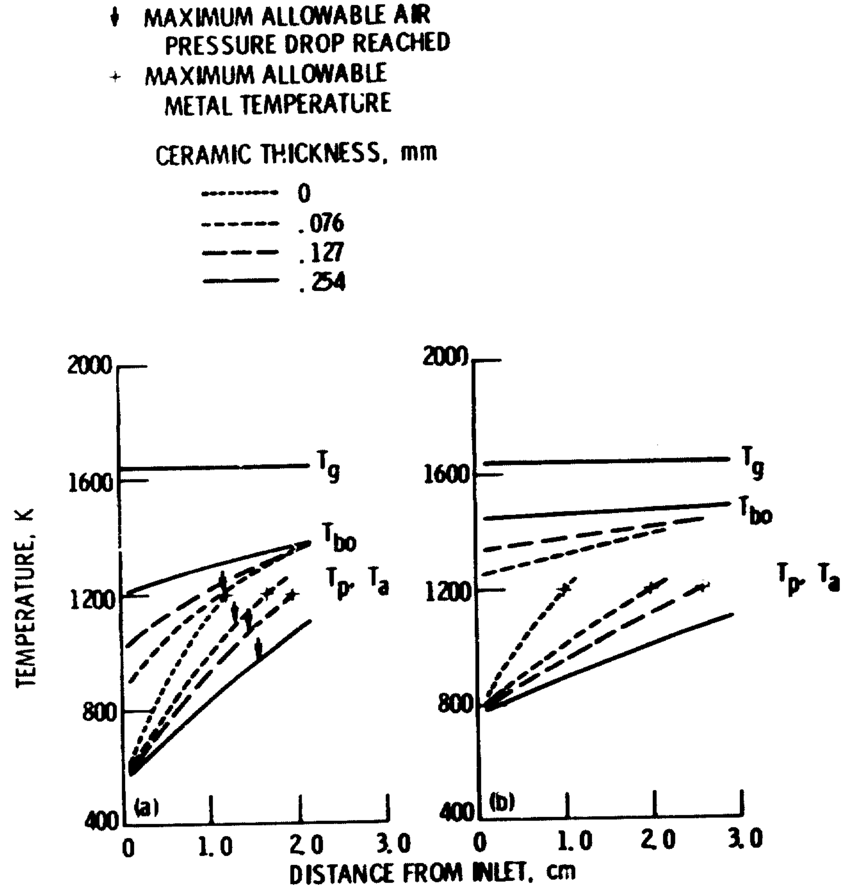

Fig. 4. Effect of ceramic thermal barrier coating thickness on spanwise temperatures of an air-cooled ceramic coated porous metal vane made of PM-1 with a metal density of 0.2. Air inlet Mach number, 0.01; gas temperature, 1644 K.

(a) Gas pressure, 10 atm.

(b) Gas pressure, 40 atm.

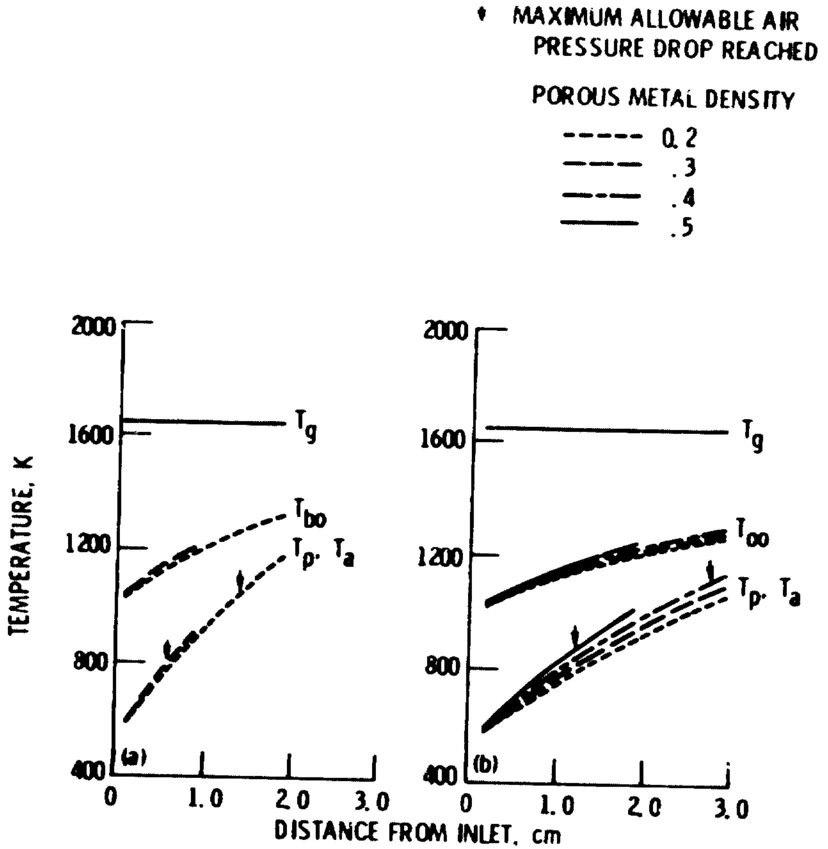

Fig. 5. Effect of Porous metal relative density on spanwise temperatures of air-cooled porous metal vanes with a 0.127 m thickness of a ceramic thermal barrier coating. Turbine inlet gas pressure, 10 atm; temperature, 1644 K.

(a) Porous metal, PM-1; cooling air inlet Mach number, 0.01.

(b) Porous metal, PM-2; cooling air inlet Mach number, 0.02

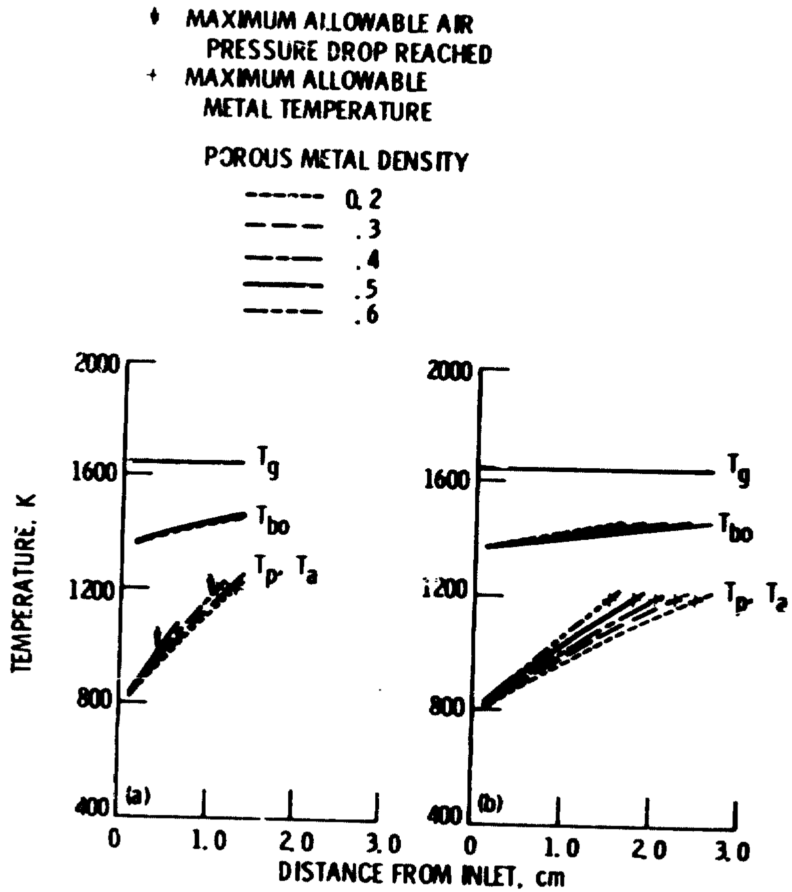

Fig. 6. Effects fo porous metal relative density on spanwise temperature of air-cooled porous metal vanes coated with 0.127 mm of ceramic. Turbine inlet gas pressure, 40 atm; temperature, 1644 K.

(a) Porous metal, PM-1; air inlet Mach number, 0.005.

(b) Porous metal, PM-2; air inlet Mach number, 0.01.